



INTEGRATION OF LCA CONSTRUCTION IN STRAW AS INSULATION MATERIALS FOR BUILDING WALL

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Burce, Roselle Adel B.
Caringal, Janna Graziella M.
Laurio, Adelheid Germaine P.
Villanueva, Daniel Kenneth

Dr. Jason Maximino C. Ongpeng

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Chapter 1

PROBLEM SETTING

1.1 Introduction

As the world continues to progress, concerns regarding the energy crisis and greenhouse gas emission (GHG) contributing to global warming increase. Buildings account for the vast majority of energy consumption worldwide. As a result, resolving this issue is critical in order to enhance energy efficiency. The use of appropriate insulation materials in the building envelope is viewed as a viable method to ensure comfort with minimal or reduced reliance on heating and cooling systems. The goal of thermal insulation materials is to slow the movement of heat. Thermal conductivity is the most important feature of insulation materials. The lower a material's thermal conductivity, the more effective it is as a thermal insulation, and thus a thinner layer is necessary to maintain an equal interior temperature (Zhou, Trabelsi & Mankibi, 2022).

The majority of thermal insulation materials are made from petrochemicals, which leads to significant energy consumption and a negative impact on the environment especially during manufacturing or production stage. Because of their excellent thermal qualities, the most prevalent thermal insulation products are made from synthetic materials such as glass fiber, mineral wool, and plastics. Their production utilizes a significant quantity of nonrenewable resources, resulting in greenhouse gas emissions and pollution. This

necessitates the adoption of more environmentally friendly or sustainable materials.

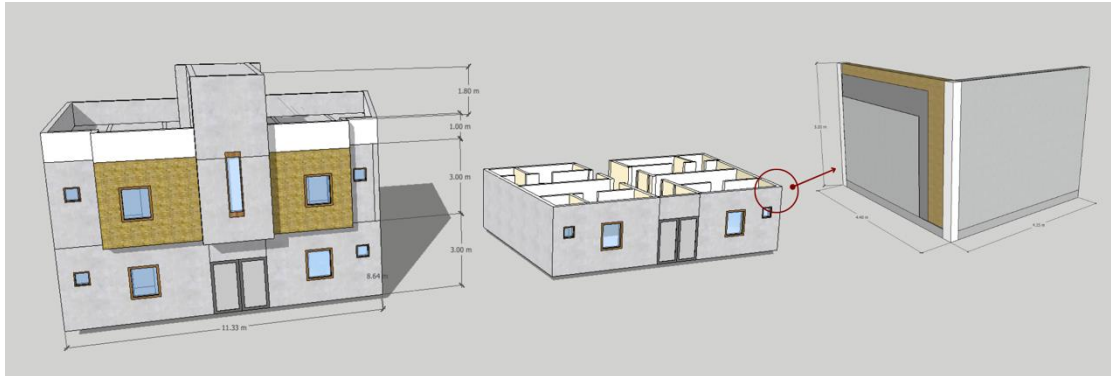


Figure 1.1 Straw Bale Construction of the Capstone Design Project

Bio-based materials, such as straw, are emerging as a promising option for enhancing the overall building energy performance while also lowering carbon footprint. In comparison to conventional construction materials, biobased materials regulate temperature and relative humidity variation to improve indoor comfort while emitting less carbon dioxide (CO₂) and lower embodied energy. Recently, there has been a growth in research on straw construction and its importance in the industry.

Agriculture waste is a carbon-neutral renewable material derived from local agricultural activities. Straws are residue from crops such as wheat, rice, corn and the like. These are abundantly produced all around the world. Rice and corn are two of the country's most important basic crops. In terms of rice output, the Philippines is rated eighth in the world. Several provinces are also considered to be the largest rice-producing region in the country (FAOSTAT, 2020). Because these resources are widely available in the country, extensive

research on their properties, effectiveness as an insulation material, and types or varieties that can be employed is required.

1.2 Main & Specific Objectives

This study aims to accomplish the following objectives:

- To analyze the environmental impact of using straw material as an insulation material on walls
- To examine the different properties that straw insulation possesses
- To compare the different types of agricultural waste such as wheat, corn, and rice husk as materials for straw insulation
- To identify which agricultural waste can be best used for straw insulation
- To compare straw bale wall from concrete hollow block wall

1.3 Hypothesis

The hypotheses for this case study are the following:

- (1) The use of straw as an insulation material on walls of buildings has a positive environmental impact.
- (2) Among all the materials, rice is the best agricultural waste that can be used for straw insulation.

1.4 Assumptions

The study assumes the following in the conduct of the study:

- (1) The data gathered indicates the same values in the Philippines.
- (2) The result yielded is applicable in the Philippines.
- (3) The data available in Simapro is accurate.

Chapter 2

METHODOLOGY

2.1 Life Cycle Assessment

Life Cycle Assessment verifies the straw bale in terms of its environmental impact as an alternative to be a sustainable insulation material. The study would be analyzed by the production of a straw bale wall. Consequently, SimaPro would help in data gathering to assess its impact on climate change, ecotoxicity, and mineral scarcity. The findings would solidify the characteristics of straw bale wall as the data would illustrate its overall impact to people, animals, and resources. Figure 2.1 describes the framework for this study.

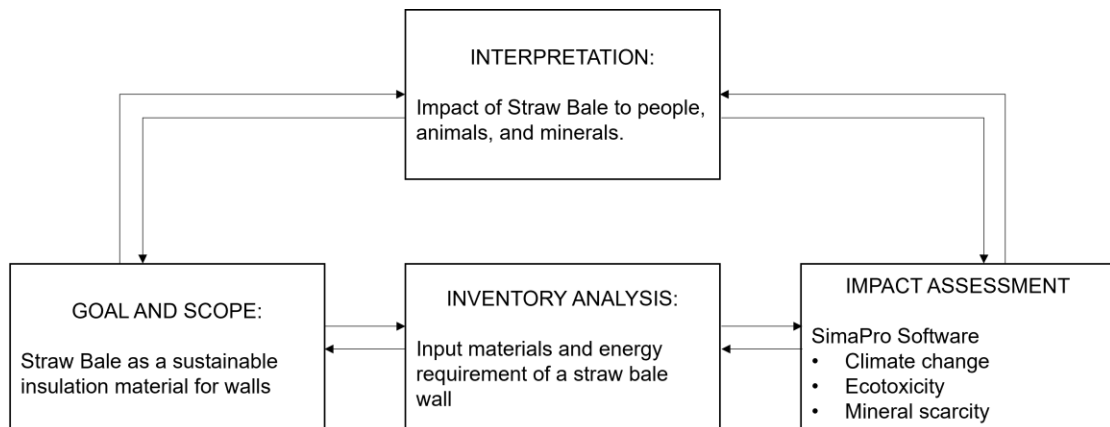


Figure 2.1 LCA Framework

2.1.1 Goal and Scope

This study will include the comparison of the concrete hollow blocks wall to straw bale wall in terms of environmental impact and costing, comparison of wheat, corn, and rice husk as materials for straw insulation, analysis of environmental impact of materials analyzed, and consideration of current utilization of the product in the Philippines. This study will focus on the impacts of transportation, electricity, and use of the mineral resources on three environmental categories, specifically climate change, mineral scarcity and human toxicity. Moreover, the agricultural materials to be compared are only limited to wheat, corn, and rice husk. Lastly, this study will only consider the feasibility of the products in the Philippines.

2.1.2 Functional Unit

The functional unit that would be used in this LCA is a 1 m² straw bale wall. The wall that would study would come from one Capstone Design Project (CDP) building.

2.1.3 System Boundary

The system boundary depicts the input parameters to create a straw bale wall. The data considered are the materials and energy requirements expressed in kilograms (kg), cubic-meter (m³), tonne-kilometer (tkm), and kilowatts (kWh). The data are more thoroughly explained in Section 2.2 as it

would be integrated in SimaPro for analysis. Figure 2.2 illustrate the system boundary for this study.

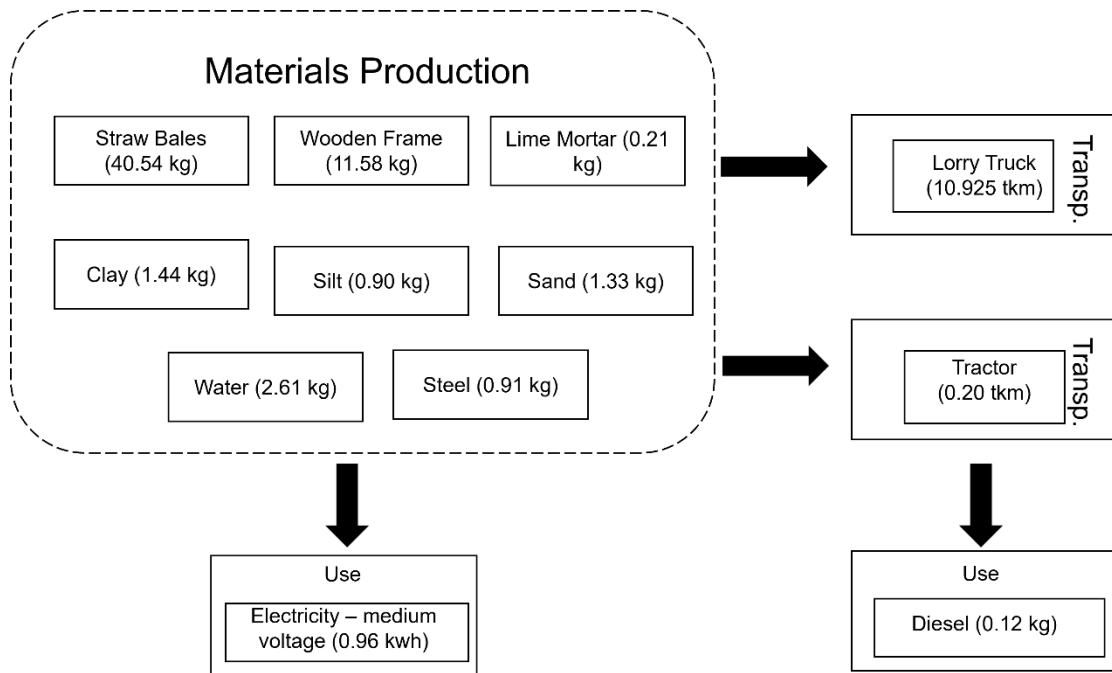


Figure 2.2 System Boundary of a Straw Bale Wall

2.1.4 Impact Assessment

The straw bale wall would be assessed by its impact on climate change, ecotoxicity, and mineral scarcity. Further, the analysis for its damage assessment would be categorized by its impact on human health, ecosystem quality, ecotoxicity, and mineral resource scarcity

2.2 SimaPro Analysis

SimaPro is a software commonly used by experts that helps in understanding the life cycle assessment of a specific material. The gathered data can measure a product's sustainability and its impact assessment in terms

of environment, human health, and minerals. As the LCA of a material can vary from simple to complex cycle, SimaPro can efficiently model it in a systematic manner. It also provides results that are fact-based and therefore contributes to the proper decision making to reduce carbon footprint of materials.

This study utilizes SimaPro to evaluate the life cycle assessment of the straw bale wall and identify the environmental load it possesses. Other data and values for specific process and composition in this study are gathered through research articles that have provided reliable sources for analysis of the construction of a straw bale wall.

In the software, there is a library filled with numerous databases that contains data. This study uses the Ecoinvent 3 - allocation, cutoff by classification - unit and Methods database. Under process, the study created a new material under insulation materials entitled Straw that pertains to the composition of straw used for the construction of the 1 m² straw bales wall. The data inputted is seen at Table 2.1 excerpted in the study of Zhou, Y., Trabelsi, A., & Mankibi, M. (2022).

Table 2.1 Composition of Different Types of Straw (% percentage)

Straw Type	Cellulose	Hemicellulose	Lignin	Water Soluble	Wax	Ash
Wheat	38.6	32.6	14.1	4.7	1.7	5.9
Rice	36.5	27.2	12.3	6.1	3.8	13.3
Corn	38.5	28.7	15.0	5.6	3.6	4.2

Another material is added in the insulation materials called Straw Bale Wall having a unit of m². The data inputted from nature is Table 2.2 and for technosphere (materials/fuel and electricity/heat) is Table 2.3. These data are obtained from the study of D'Alessandro, Bianchi, Baldinelli, Rotili, & Schiavoni. (2017) which entails the materials used for its construction and the materials' transportation process.

Table 2.2 Materials contained in 1 m² straw bales wall.

Item	Element	Amount	Unit Metric
Straw Bales	Straw	40.54	kg
	Polypropylene	0.05	kg
Wooden Frame	Wood	11.58	kg
	Steel	0.91	kg
Interior Plaster Earth	Clay	0.96	kg
	Silt	0.60	kg
	Sand	0.84	kg
	Water	1.44	kg
Exterior Plaster Earth	Clay	0.48	kg
	Silt	0.30	kg
	Sand	0.42	kg

	Water	0.72	kg
Lime Plaster	Natural Hydraulic Lime	0.25	kg
	Sand	0.75	kg
	Water	0.37	kg
Coating	Premixed (Natural Hydraulic Lime and River Sand)	0.21	kg
	Water	0.06	kg
Wall Assembly	Water	0.02	m ³

Table 2.3 Energy requirements per 1 m2 straw bales wall.

Item	Element	Amount	Unit Metric
Straw Bales	Diesel fuel for baling	0.12	kg
	Straw bales transport by tractor	0.20	tkm
Wooden Frame	Wood transport by truck	9.85	tkm
	Steel transport by road	0.005	tkm
Plasters	Hydraulic lime transport by truck	0.41	tkm
	Sand transport by truck	0.03	tkm
Wall Assembly	Electricity	0.96	kWh

Under impact assessment, the method used for its LCA analysis is LC-IMPACT | marginal pref. | all imp. | 100y. As the data has been completed, the

calculation for its network and impact assessment are presented as seen in Figure 3.9 to 3.11 in Results and Discussion section.

For the comparison of Concrete Hollow Block (CHB) wall, another material is created under process entitled “Concrete Hollow Block Wall”. The data inputted is seen at Table 2.4 is the materials requirement to create a 1 m² CHB wall with concrete, plaster and mortar mix Class C, and a hollow block with thickness of 4” as it is the common thickness used in the Philippines (Cadalin, 2015).

Table 2.4 Materials contained in 1 m² CHB wall.

Item	Element	Amount	Unit Metric
CHB	CHB	234.50	kg
Mortar Mix (Class C)	Sand	71.78	kg
	Cement	15.76	kg
Plaster Mix (Class C)	Sand	39.60	kg
	Cement	8.64	kg
Steel (10 db mm)	Steel	2.016	kg

Chapter 3

RESULTS AND DISCUSSION

3.1 Straw Bale Wall



Figure 3.1 Nebraska or Load Bearing Wall Style

The construction of straw bale method can use 2 techniques known as Nebraska or load bearing walls style and post and beam. Nebraska or load bearing walls is the traditional method where straw bales are attached to the foundation and piled up until its roof framing. With this, the weight of the roof would be endured by the straw bale. The reason for this set up is because of the lack of resources for lumber, saving it for roof framing. The advantages of this technique are there would be less wood to use, no framing resulting in faster construction, and utilization of carpentry skills is not required. Although,

its disadvantage is limited installation of doors, windows, and building size as the straw cannot have the strength to support it, and an increase of work as bracing is needed for the straw to be stacked up.



Figure 3.2 Post and Beam Method

However, in modern construction, the post and beam method is created and more developed than load bearing wall. The difference between the two is that the post and beam has a frame to help support the loads. The frame can be made out of steel, wood, and concrete blocks. In this way, the straw bale would only bear its own self-weight. The advantages of post and beam are its ability to install numerous doors and windows and can support larger building size, its uncomplicated ability to level the building, and its durability and rigid structure thus a faster approval for its application process. For its disadvantages, it is more expensive compared to load bearing wall, carpentry

skills are needed to ensure the straw bales are properly braced and fitted in the framing of the post and beam for assurance of a rigid structure.

With Nebraska style, the traditional method may not be suitable for acceptance in engineering. Professionals do not acknowledge straw bale construction as there are discrepancies in the technical data for straw bale. This led them to have a dilemma on what to input on simulation models. Hence, Post and Beam style are more accepted by them as it uses other materials than straw bale, conforming to national building codes. The popularity of doing Nebraska style is due to the touch of personality and design the wall brings to the overall structure of the infrastructure. The angle lines and perfect upright position of walls are difficult to achieve in Nebraska Style, in which it is frowned upon by engineers and architects; however, self-builders caught the attention of the style and aesthetic effect it brings to the structure.



Figure 3.3 Lime Based Plaster (Left) and Clay or Earth Based Plaster (Right) on Straw Bale Construction

There are two types of plaster that can be used for straw bale construction. One is lime-based plaster which is commonly used as it provides breathability and durability in the structure, and it is low maintenance. Its low

maintenance is because it avoids cracking of the wall leaving it a longer duration of a smooth wall. Before plastering, the steel and timber or polypropylene fibers are meshed onto the wall. Afterwards plastering is done by applying 2 to 3 lime and sand coats through using a plaster pump on the wall. Another 2 additional coats are applied when doors and windows have been built. The other type of plaster is clay or earth-based plaster that is used for external and internal plaster. It has a capability to be much breathable compared to lime plaster, because of its capability to maintain a 40% humidity. This humidity prevents mold forming in the housing. Further, clay plaster holds more moisture compared to straw, resulting in the clay plaster to absorb the moisture and release it, preventing the straw bale from absorbing the moisture, prolonging its good condition. For application, plastic or fiberglass mesh is used and metal mesh or wire is avoided as it rusts easily, damaging the plaster. There are two systems used which are sand-clay plaster and straw clay plaster. Sand-clay plaster uses 2 to 3 coats, and a plastic or fiberglass mesh is applied to act as reinforcement. While for straw clay plaster, there is no mesh as it only uses the supports of the large quantity straw fiber (Henderson, 2015).

Straw is widely regarded as a low-cost building material around the world. It has many applications, and with advancements in technology and developments in the field, straw building construction has become a popular method because it provides low-carbon and affordable solutions in construction. One of the earliest examples of straw bale construction can be found in Nebraska, USA, and it has since gained popularity in the industry,

having been adopted in continents and countries such as Europe, South Africa, Chile, both North and South America, and even Pakistan. The design of straw bale buildings has evolved in tandem with the various modernization layouts of houses. A modern straw bale building design is depicted in the figure below. In order to use straw as insulation, windows and openings must be detailed in the plan and design (Walker & Maskell, 2016).



Figure 3.4 Modern Straw Bale Construction: BaleHaus Located in the University of Bath, England

Straw bale construction is also popular in Asian countries such as Thailand and Japan. Rice straw is a common and local material used in Japan because rice cultivation is widespread. The actual number of straw bale buildings in Japan is increasing year after year. In this country, straw bale construction focuses on non-load bearing structures with loads carried primarily by the frame and straw bales used only as an infill. However, several non-load-bearing straw bale walls are still being built. Some examples of these can be found in Japan, as shown in the figures below.



Figure 3.5 Construction of Non-Load Bearing Straw Bale Walls in Minamiboso and Toyama City, Japan



Figure 3.6 Straw Bale Structure in Thailand

In the applicability of construction of Straw Bale Wall in the Philippines, it would be difficult for execution for large building size. With different variations of its parameters in its properties, the unsteady-state condition of straw bale is not thoroughly investigated yet, more so on warm countries (D' Alessandro, 2017). This is concerning as it a straw bale house may be hard to be accepted, as it can fail in national building code. Hence, a laboratory assessment of using straw bale for warm countries is needed to solidify its capability to support large loadings. However, there is a chapel constructed using the mixture of rice straw and lime in its wall and bamboo trunks for its post and trusses (Archinspire #28: Earth Chapel, 2012). It is Bacolod City, inside of the University of Negros

Occidental – Recoletos, known as Earth Chapel, as seen in Figure 3.7, that promotes the advocacy for preserving the environment.



Figure 3.7 Earth Chapel - Mud Mixed Straw and Lime Wall in Philippines

3.2 LCA Interpretation of Straw Bale Wall

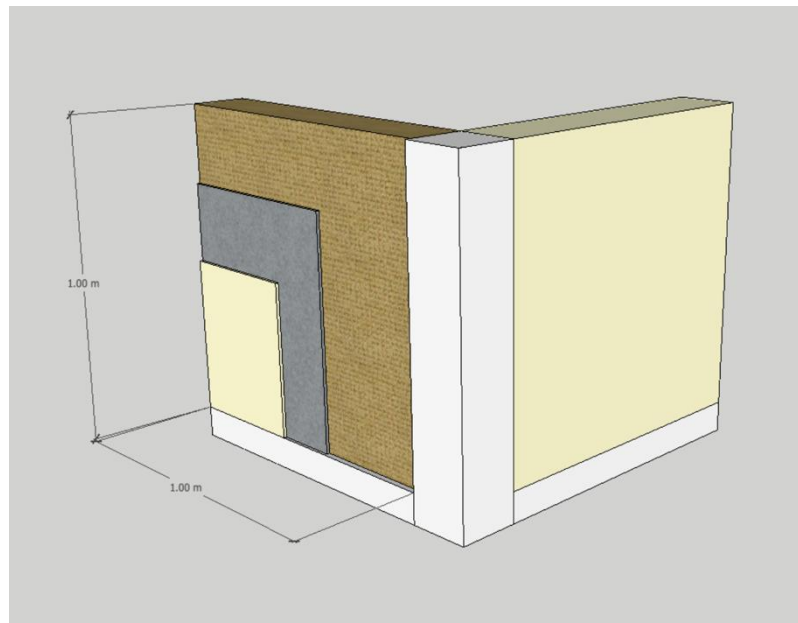


Figure 3.8 1m² Straw Bale Wall (Functional Unit)

Figure 3.9 presents the straw bale wall process network that is created through the help of SimaPro. The process network is expressed in percentage, depicting the disability-adjusted life year due to climate change. Figures 3.9 to

3.11 show the results obtained from SimaPro. Shown in Figures 3.10 and 3.11 is the impact and damage assessment (in percentage, %) of the different materials and transportation involved in making a straw bale wall to different environmental categories. In all categories the use of electricity (gray graph) has the highest negative impact in the whole procedure. Transportation (red, blue, and yellow graph) is the most common negative and if assessed cumulatively, is the highest. Furthermore, the production of light mortar (light green graph) and straw bale (dark green graph) has the least impact on almost all categories except for mineral resource scarcity.

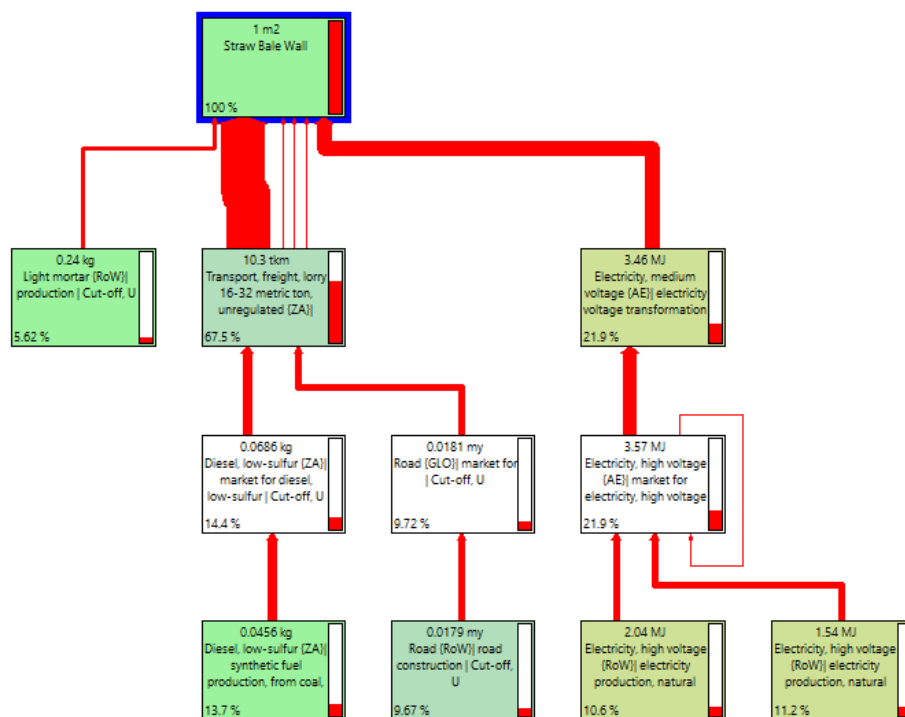


Figure 3.9 Straw Bale Wall Process Network

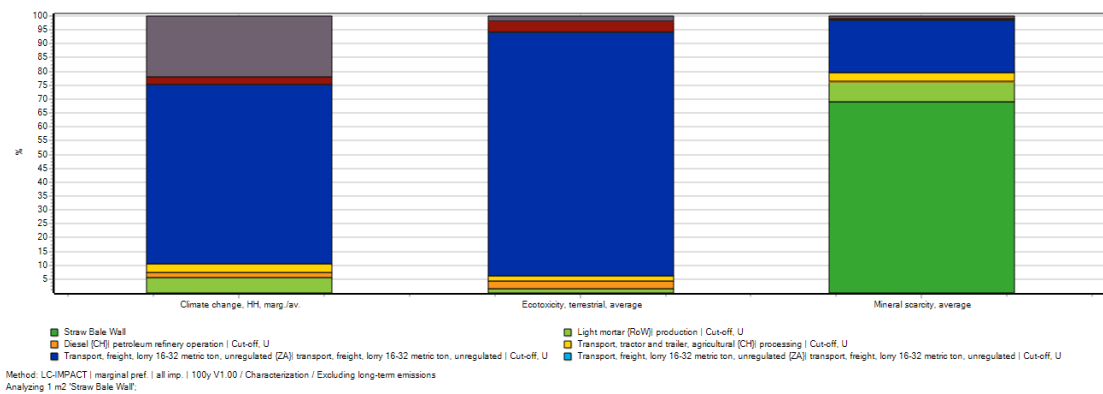


Figure 3.10 Impact Assessment of the Straw Bale Wall

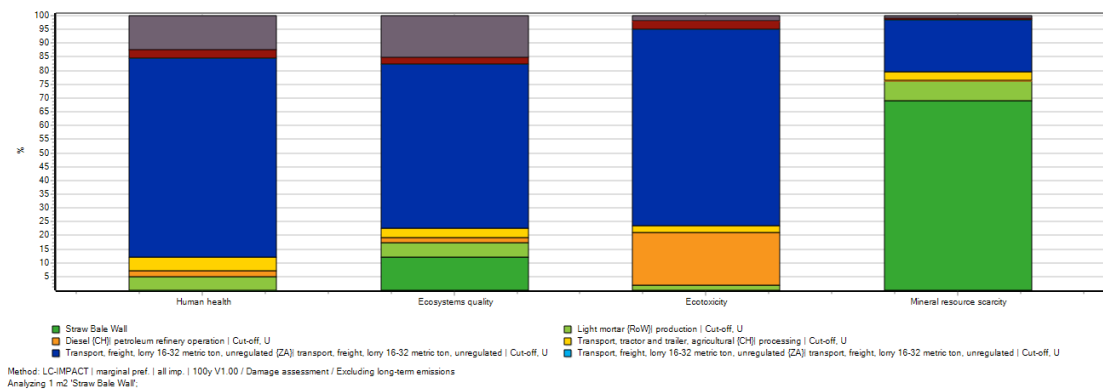


Figure 3.11 Damage Assessment of the Straw Bale Wall

3.2.1 Environmental Impact

This study will focus on the impacts of transportation, electricity and use of the mineral resources on three environmental categories, specifically climate change, mineral scarcity and human toxicity. Climate change is the long-term shifts in temperatures and weather patterns. It may be caused by natural events such as variations in the solar cycle but for the past two centuries human activities, such as the burning of fossil fuels like coal, oil, and gas, have contributed to these shifts (United Nations, 2020). The LCA on SIMAPRO showed that the use of electricity has the highest percentage contribution to

climate change and is followed by transportation. Nevertheless, various studies have mentioned that the use of straw bale in construction has given positive impacts on the environment. It has reduced the use of bricks by two thirds. Bricks require a lot of energy to manufacture, thus, contributing a lot to climate change. The utilization of straw bale has decreased CO₂ emissions per house of the same size by 0.6 to 1.2 tons each year. Moreover, construction transportation has contributed about 2.4% to 5.5% of CO₂ emissions. However, Gonzales (2014) mentioned that transportation impacts would be low if locally available straw bales would be utilized. With regards to mineral resources, a paper by Garas et al., (2009) mentioned that in Egypt, there is a surplus of in rice straw. However, due to lack in compressors, farmers lead to quick and costless solution such as burning. Because of this, the authors studied how much one can save in using straw bale wall compared to the traditional cement hollow block wall. Results of their study show that about 40% of the cost is saved. These studies show that excess straw bale resources are sustainable, cost-efficient, and environment friendly.

3.2.1.1 Transport

Construction transport refers to the delivery of materials, machinery, and equipment to the project site and the transport of material waste out of the site. Studies showed that about 2.4% to 5.5% of CO₂ emissions come from construction transport while others indicate that it constitutes about 16% of the total emissions from a project come (Fredriksson & Sezer, 2021). Vanova, et.al

(2021) mentioned that straw-based construction gives a positive impact on construction transport. Traditional buildings that made use of local raw material required minimal processing and transportation. Gonzales (2014), focusing on straw bales and their life cycle, found that the embodied energy of straw bales was 5.8% and 19.8% lower than that of a burnt brick and cement block, respectively. Furthermore, he demonstrated that travel distances of typical masonry construction materials significantly increased overall environmental harm. Thus, emphasized the need of renewable agricultural products in reducing construction material impacts. These shows that transportation impact would be low if locally available straw bales were utilized.

3.2.1.2 Electricity

In their website, World Habitat (2018) mentioned that the utilization of straw bales has reduced the number of bricks used in construction by two-thirds. Unlike straw bales, bricks require a lot of energy to manufacture. On cold days, a straw bale house burns 5 kg less coal than a masonry structure. Straw bales houses are 68% more efficient than masonry houses of the same size. Furthermore, CO₂ emissions per house decrease by 0.6 to 1.2 tons each year depending on the house size and severity of winter. By reducing the number of bricks in construction, there is an increase in soil conservation and a decrease in the usage of the firing fuel. Straw bale walls provide excellent insulation, lower fuel costs, CO₂ emissions, and consequently air pollution while having a low embodied energy.

3.2.1.3 Mineral Resources

Traditional construction involves the use of cement hollow blocks, a material that uses cement which is made up of limestone and clay. However, various study has stated that there has been a shortage in cement over the years. In relation to this, other than the mentioned studies in the previous sections, the use of straw bale in houses can save about 15% of wood. It reduces construction waste and is biodegradable or reusable. It is a waste produces and any excess can be utilized. It reduces the use of wood and cement, particularly in load-bearing straw bale designs (Kubba, 2017).

3.2.2 Damage Assessment

Human health

Straw bale walls provide numerous benefits not only because of its low-cost construction but it also presents advantages for human health. This can be seen as shown in Figure 3.11. Due to their potential to be renewed, natural materials have less effect on the environment. Straw bales contain less toxins than the usual building materials used, making it a better alternative. This criterion is crucial because it also has an impact on the environment. The building of straw bale walls, a prime example of sustainable construction, aids in lowering carbon dioxide emissions. It is crucial to consider how a material may affect the workers who will be constructing the structure and the health of the occupants. Because the straw wall system is made of entirely natural and recyclable materials, less energy is also consumed overall (Brojan et al., 2013).

Mineral Resources Scarcity

Based on Figure 3.11, mineral resource scarcity of straw bale wall is large as it still utilizes resources for its production. With the growing number of resource scarcity, straw bale wall provides a sustainable alternative in construction as opposed to conventional materials. Compared to other wall materials, it replaces components such as cement, steel, and wood for load bearing. As its main component is the utilization of agriculture waste whereas its energy production for a ton of straw reaches up to 120,000 KJ compared to an energy production of 6,150,000 KJ per ton of steel. Hence, there is a decrease of usage in steel and wood, cutting down logging and extraction of minerals (Bendapu et al, 2012). In the Philippines, there is total area of 6.83 kha of forest lost in the country and 43.6 kha of area is lost because of commodity and 822 ha is lost because of urbanization in year 2021. As for mining, there would be 12 new mining operations that would be launched this year, 2022 (SMM, 2022). With the increase of resource scarcity in the country, straw bale can help alleviate the growing impact on resource scarcity.

Ecosystem

Another disadvantage of traditional construction is its negative impacts on biodiversity. Air, water, noise, and light pollution are just some of its impacts on wildlife. As mentioned, the use of straw bale wall decreases CO₂ emission, thus decreasing impact in air pollution. In addition, its utilization in construction decreases waste which positively impacts the ecosystem as waste has become a global problem. Kubba (2017) mentioned that straw bale is environmentally

friendly since it does not require toxic treatment, thus, reducing effects of the chemicals that concrete uses. For years, the construction industry has been studying and looking for alternatives and sustainable solutions to lessen the construction impacts in the environment. The properties that straw bale possess makes it a good construction material alternative.

3.3 Concrete Hollow Blocks

Concrete hollow block, also known as CHB, is one of the most used types of walling material in the Philippines. It is used and has become a part of residential structures throughout the country, due to its low cost and speed of installation. Aside from this, it has good properties in terms of fire resistance and mechanical resistance. A typical hollow block mixture includes Portland cement, water, sand, and gravel (aggregates). It is compacted by high pressure and vibration which contributes to its strength to resist several loads.

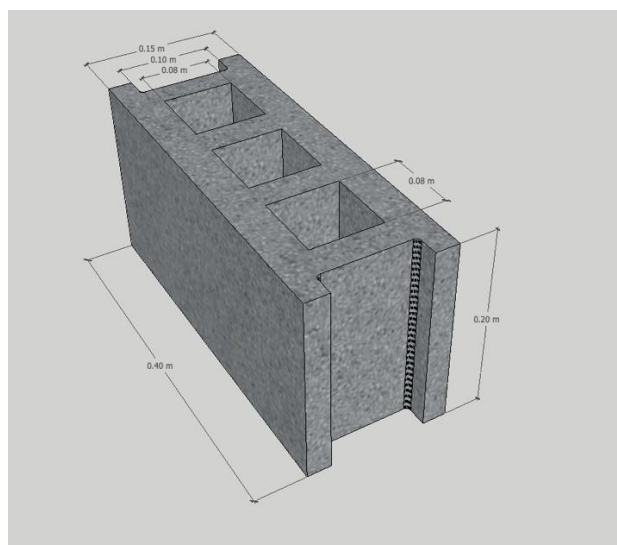


Figure 3.12 Concrete Hollow Block (CHB)

With the country's rapid urbanization and an increase in various concerns such as waste and pollution, environmental sustainability has recently become a primary concern, particularly in industries such as construction and manufacturing. This necessitates the search for alternative materials that are both low-cost and, most importantly, environmentally friendly (Ignacio, Acierto, Camba, Gomez & Ozaeta, 2020).

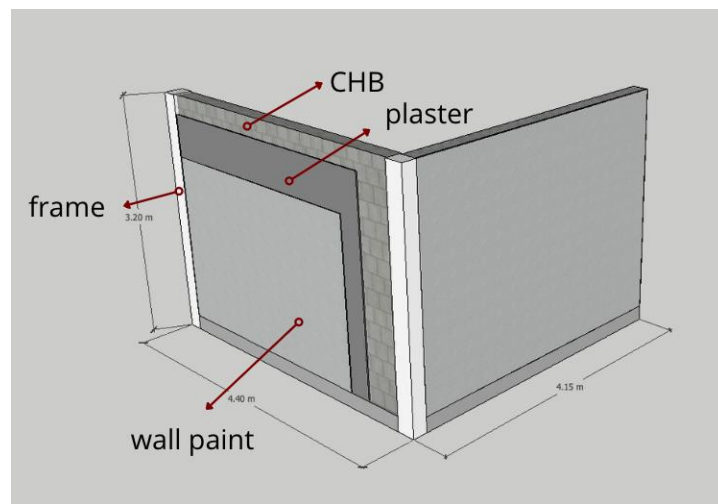


Figure 3.13 Layers of a CHB Wall

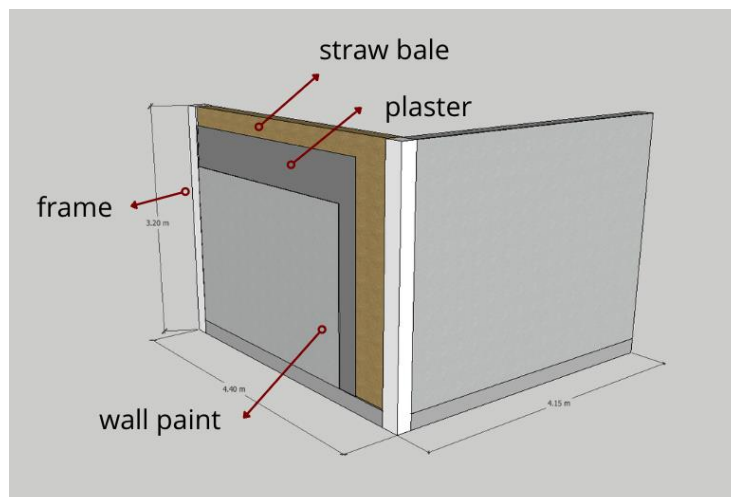


Figure 3.14 Layers of Straw Bale Wall

Figure 3.13 shows the layers of a CHB wall that is commonly used in the Philippines. Usually, the procedure begins with concrete hollow blocks being layered inside the wall frame and, sometimes, it is reinforced with steel bars. Then, the blocks are covered with plaster to smoothen its outer surface. Lastly, the walls are painted with the desired color of the client. To mitigate the negative impacts of the use of CHB in construction, straw bale can be used as an alternative (refer to Figure 3.14). As various research have claimed the positive impacts of straw-based construction, it implies that this agricultural waste can be used a replacement of CHB when making walls. The following sections will discuss more about this implication.

3.3.1 Comparison to Straw Bale Wall (LCA)

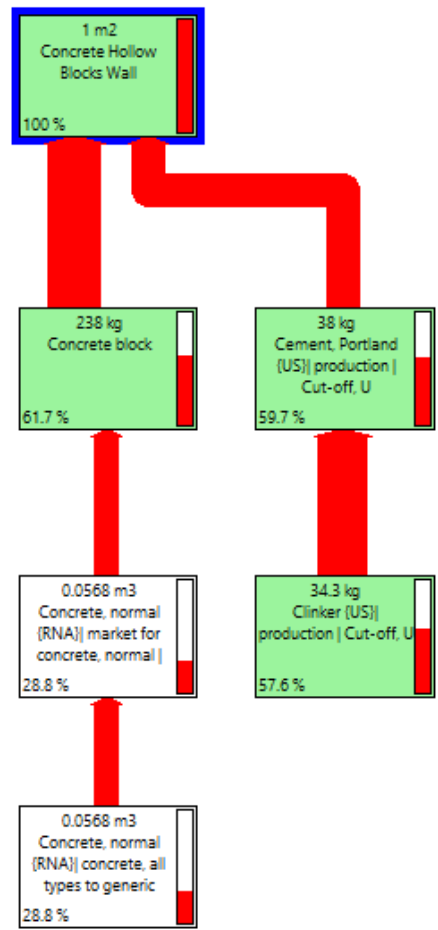


Figure 3.15 Network Diagram

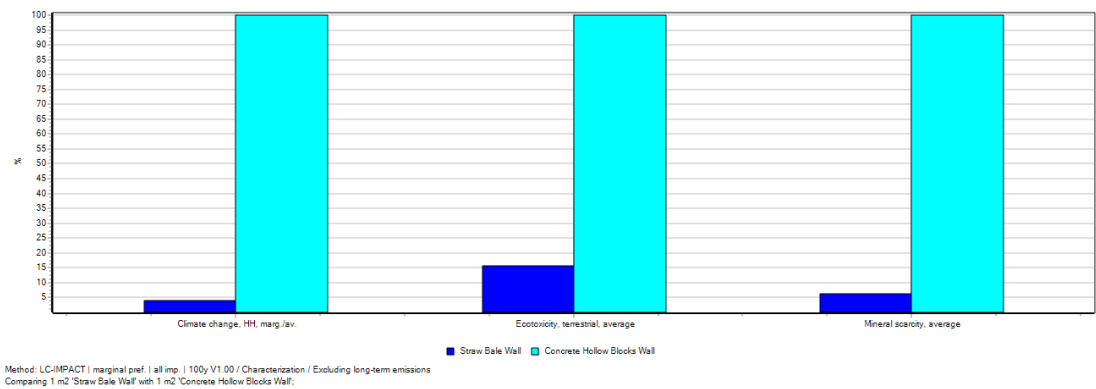


Figure 3.16 Comparison of Impact Assessment between Straw Bale Wall and CHB Walls

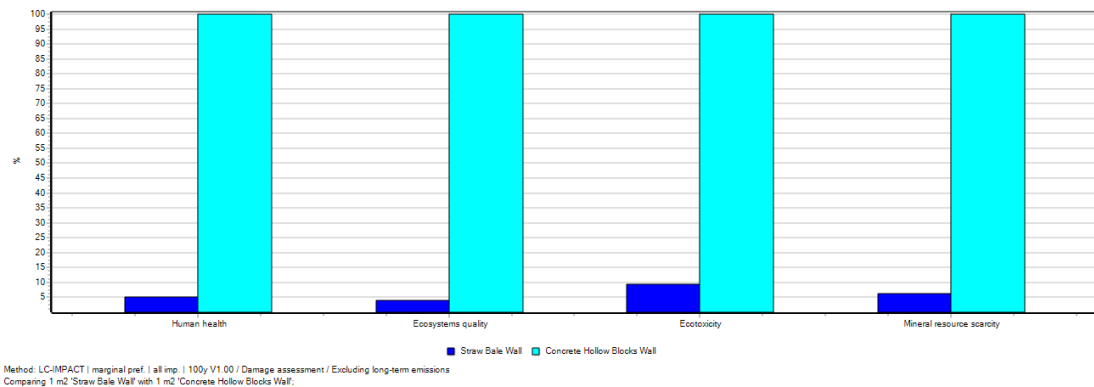


Figure 3.17 Comparison of Impact Assessment between Straw Bale Wall and CHB Walls

The figure depicts the life cycle impact assessment of 1 m² straw bale walls and 1 m² concrete hollow block (CHB) walls conducted in SimaPro. 1 m² was used and established in order to clearly distinguish and determine the difference between the two in terms of impact. The bar graph in dark blue represents straw bale wall while the light blue bar graph represents concrete hollow block (CHB) wall. It is very evident that CHB contributes relatively more impact negatively into the different categories and aspects compared to that of a straw bale wall. When compared to other factors such as climate change and mineral scarcity, straw bale walls have a relatively high percentage of ecotoxicity. The straw bale was shown to have low values of primary energy and global warming potential compared with the traditional mineral insulation materials.

Table 3.1 Comparison for Thermal Conductivity, Embodied Energy and Global Warming Potential.

Number Required per 1m ² of wall	Thermal Conductivity (W/(m·K))	Thermal Transmittance (W/(m·K))	Embodied energy (MJ/m ²)	Global Warming Potential (kgCO ₂ -eq/m ²)
11 concrete blocks	0.64	3.2	169	9.6
3 straw bales	0.07	0.16	28	2.5
3 half straw bales	0.07	0.32	14	1.3

Based on the results produced from the performed analysis in the SimaPro software and the table above from the study conducted by González (2014), the straw bale was shown to have low values of primary energy and global warming potential compared with the traditional material, concrete blocks. Straw bales have a low thermal conductivity, as measured by the values in the table, indicating that heat does not easily pass through them. A low thermal conductivity indicates that it is considered as a good insulating material.

3.3.2 Cost Analysis

According to PhilConPrices (2020), the price for Concrete Hollow Block (CHB) 4" per piece is PhP 12.00 and Php 18.00 per piece for CHB 6". Another data by PhilConPrices (2019) shows the prices for CHB in Luzon where CHB

Load Bearing – 4" is PhP 19.31 per piece, PhP 22.89 per piece for CHB Load Bearing – 6" .

In producing a 1 m² wall with a CHB thickness of 4 inches with Mortar Mix Class B and Plaster Mix Class C, 12.5 concrete hollow blocks are required. As for the mortar mix that will be used, this would require 0.0435m³ of sand and 0.394 bag of cement (15.76kg). Meanwhile for plaster mix, 0.024m³ of sand and 0.216 bag of cement (39.60kg).

Table 3.2 Cost Analysis for CHB Wall

Cost Analysis for 1 m ² CHB wall	
Element	Price (PhP)
CHB	241.375
Sand	96.66
Cement	159.82
Steel (RSB)	80.64
Total	PhP 497.86

The cost below is the cost that a 1 m² of straw bale would incur. The most influential factors are straw, wood, lime mortar and steel. The price of wood is an influential variable factor. The variability of wood is because the analysis for Fir tree (The tree that would be used in plywood) states that the density of the tree is 529 to 737 kg/m³ (Matmatch, n.d.).

A 3/4" x 4' x 8' – Ordinary Plywood would have a price of 1112 pesos per piece (PHILCON PRICES, n.d.). Polypropylene would be around USD

1592/ton-USD 1702/ton (ChemAnalyst, n.d.). Sand have a density of 1430 kg/m³ and Silt would have density of 1380 kg/m³ (StructX, n.d.).

Table 3.3 Cost Analysis for Straw Bale Wall

Cost Analysis for 1 m ² Straw Bale Wall (Php/m ²)			
Element	Low Estimate	Mid Estimate	High Estimate
Straw	364.86	364.86	364.86
Wood	308.51	369.16	429.82
Steel	36.40	36.40	36.40
Lime Mortar	124.97	124.97	124.97
Sand	2.22	2.22	2.22
Silt	0.25	0.25	0.25
Polypropylene	4.39	4.54	4.69
Total	841.61	902.41	963.22
Ratio to CHB cost	1.69	1.81	1.93

Overall, we would find that a straw bale wall is 69% to 93% more expensive than a CHB wall. Although this may seem small, given both the tight margins of construction, the fact that trifling matters are given greater importance (Forsyth, 2009) and the fact that there is a sense of apathy with regards to concerns about climate change (Antadze, 2018). Moreover, using CHB blocks would not give any short-term impact with regards to the construction of a single house. The impact of unsustainable construction is only felt in the very large scales, in the scale of the construction of multiple different groups of subdivisions.

3.4 Properties of Straws as an Insulation Material

According to the research of Zhou, Trabelsi and Mankibi (2022), when examining straws as an insulation material, it is important to analyze the following properties: (1) Thermal insulation, (2) Moisture, (3) Mechanical, (4) Durability and (5) Fire resistance.

3.4.1 Thermal Insulation

A material's thermal conductivity refers to its ability to conduct heat. The lower the thermal conductivity of a material indicates that it can be considered as a good insulating material. Specific heat capacity, on the other hand, describes the ability to store heat in a way that allows it to increase or decrease the indoor temperature. Numerous studies indicate varying values for straw bale thermal conductivity, with 0.03 W/(mK) being the lowest and 0.1 W/(mK) being the highest. The values are influenced by various factors such as straw type, bale density, temperature, and relative humidity. Thermal conductivity and density have been found to have a positive direct relationship. Additionally, high fiber content and large fractions or portions of fibers would result in lower thermal conductivity values. In terms of its relationship with temperature and moisture content, thermal conductivity rises as these variables rise.

3.4.2 Moisture

Moisture concentration inside a building material can have an impact on heat flux and heat capacity. The moisture content of straw bales is affected by

the surrounding environment, taking into account factors such as relative humidity and temperature. Straw bales' water vapor resistance factor was shown to be closely associated with their density, with a lower density resulting in a lower water vapor resistance factor due to greater open gaps between straw fibers. Additionally, straw bale water absorption is significantly associated with porosity and hygroscopicity.

The moisture properties of straw bales and straw composites have been observed to be influenced by various factors. It includes, fiber content, nature of the fiber (hydrophilic), its size and thickness, and porosity. The different types of straws have no effect on its moisture absorption. In the study conducted by Yin, et al. (2018), the cross-sectional area of rice and wheat straw is compared and analyzed for its impact on its moisture properties. The results of the experiment revealed that there are no physical distinctions between the two and that both have a negligible impact in terms of moisture content.

3.4.3 Mechanical

The mechanical performance of straws is essential. Straw bales' mechanical behavior is determined by two fundamental parameters: strain ϵ and modulus of elasticity, E . Various research reveals that straw bales are highly deformable. The study of Lecompte and Le Duigou (2017) shows that straw bales are very ductile as no breakage was observed in the compression directions of the experiment conducted. Aside from this, straw bales also exhibit a non-linear stress-strain relationship. Due to fewer voids in the composites,

increased density can achieve better mechanical performance. Straw bale mechanical properties can also vary depending on the type and source of the straw, as well as the fiber sizes and treatment procedures used. Furthermore, plastering with lime, clay, or cement can provide additional reinforcement. Using a plaster would improve the load-bearing capacity of straw bales. Its strength would be determined by the plaster's compressive resistance and thickness (Koh & Kraniotis, 2020).

3.4.4 Durability

The durability of the straws would be an important factor. Durability determines how much it could outlast the forces of nature before it would need to be replaced. Since durability could be increased by over-designing the thickness of the insulator in order to hedge against natural ablation, the insulating straws would be designed as needed and the losses in the capacity to insulate over time would be taken instead.

Durability would be of an important concern since that would also determine the life cycle of the straw bale. An insulator that is too weak may end up being a poorer choice to another insulator that, although may need more thickness to perform at the same rate as another, but however, would last longer. Plaster is chosen instead of drywall due to its higher durability. (Mar. 09 & 2022, 2022; Navon et al., 1996)

3.4.5 Fire Resistance

As for fire resistance, it is a vital component to consider as a building material must be evaluated with regards to safety issues. Different metrics, including flame spread, are used to assess the fire resistance of materials. One of the primary problems for straw bale construction is fire safety, especially given the flammability of loose straws. Compacted straw bales, on the other hand, appear to be more resistant to temperature rise and flame spread. The process of compaction or compression contributes in the reduction of the material's oxygen content and combustive agent.

Furthermore, the act of plastering (used for coating and protection) straw bales, whether externally or internally, can improve its fire resistance. According to the findings of a study, a plaster layer with a thickness of approximately 40 mm on the outside and inside was able to endure severe cracking of the layers under the conditions evaluated, which included exposure to a heat flux of 29 kW/m². This is due to an insulating barrier between the straw bale and the heat source. An unplastered straw bale sample was also exposed to the similar circumstances; however, it resulted in material ignition (Apte, Paroz & Bhargava, 2004). Several fire resistance tests have been conducted in accordance to different standards and it shows encouraging results. The plastered straw bales wall was resisting the transmission of flame and heat for several hours (Džidić, 2017).

3.5 Comparison of Different Types of Agricultural Waste as an Insulation Material

The agricultural waste that can be best used for straw insulation in the Philippines is the rice husks. This is since rice is used frequently here. Corn and wheat husks would be favorable to use in regions with temperate climates, but Philippines is in a tropical climate (Beck et al., 2018).

Since mineral resource scarcity is of the greatest concern in the creation process, rice husks would be the preferable agricultural waste. Moreover, since transportation is the main concern, the lower transport cost of rice husks would make it more profitable.

Although corn husks might look to still be a fair second choice since we also use corn wherein the corn is removed from the husk near the distribution in the product, the transportation cost for the endeavor should not make it more affordable when considering the overall impact to the system. Nevertheless, it is expected that it would still be more profitable in certain local situations since foreign facing infrastructure might be made more efficient than methods that look at acquiring from local resources.

The results in SimaPro states that the straw bale wall is the greatest contributor to mineral scarcity. This would be interpreted as the choice of the material determines the scarcity of the wall rather than the transportation methods. Nevertheless, transportation may become a factor with regards to the

availability of the wall as initiatives are created to reduce impact to climate change.

Chapter 4

Conclusion and Recommendation

The environmental impact of using straw material as an insulation material on walls was analyzed using SimaPro. The different properties that straw insulation possesses was examined. Consequently, the different types of agricultural waste such as wheat, corn, and rice husk as materials for straw insulation has been compared. It is concluded that the best agricultural waste to use in the Philippines is rice husk.

The agricultural waste can be best used for straw insulation is identified. It is the rice corn husk. This is because material scarcity and transportation are the major considerations for the selection of which straw bale wall to choose. It just happens that Philippines has a lot of rice and therefore, it would have considerably more rice husks that are located nearby than corn husks and wheat husks.

The straw bale wall was compared with concrete hollow block (CHB) wall. It was found that straw bale walls are between 69% to 93% more expensive than CHB walls. The rice husk straw bale wall is the most eco-friendly among the different types of agricultural waste. However, every other wall is considerably a promising alternative for a CHB wall especially given the low impact to the environment of straw bale walls.

The superiority of straw bale walls over CHB walls needs to be investigated further due to the seemingly paradoxical observation of the preference of CHB walls. If the CHB walls are that much more harmful to the environment as the SimaPro results claim, then straw bale walls should have been used in more projects. However, the fact that straw bale walls are 69% to 93% more expensive than normal walls convince people to stick with using CHB. Reason for a higher price for the materials for a straw bale wall is because of lack of market for straw bale increasing its price value, especially in urban areas. Hence, it is recommended that the study can further delve in analyzing the market for the materials in the Philippines to create a more economical pricing for it.

A comparative analysis should be done further in SimaPro, namely an investigation between the different types of agricultural waste as an insulation material. Although it is a good starting point to see that the transportation and scarcity is the decisive factor for the viability of the material, an LCA comparison between them would have been more beneficial to settle the debate and even find reasons for preference other than with regards to the proximity and transportation cost of the materials.

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